11.—The Yarri octahedrite iron meteorite

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Abstract

The Yarri meteorite was probably found near Yerilla, Western Australia in 1908. It is a small iron of medium octahedrite type with typical constitution and chemical composition. Acicular structure in the kamacite, faulting and other fractures were the result of extra-terrestial shock. The effects of shock and of aerodynamic heating on the hardness of the kamacite and taenite have been examined. No other irons known from the general region of the find have close resemblance to Yarri.

Introduction

Salient details of the Yarri meteorite have been given by McCall and de Laeter (1965), the original source of information being the catalogue of the collection of the Geology Department, School of Mines, Kalgoorlie. The meteorite was catalogued as specimen No. 3015 on November 2, 1908, an iron of weight 3 lb 5½ oz which had been received as a "determination" (a specimen submitted by a prospector for identification). The locality is shown as "Yarri. 8 miles from Yerilla", but the latter portion of the statement is clearly an addition and it makes the locality statement quite anomalous because the Yarri and Yerilla gold-mining townships (since abandoned) were nearly 40 miles apart (Fig. 1).

The confusion probably stems from the natural reticence of the prospector to disclose the locality of material hopefully believed to be valuable. To this day, some of the samples received for determination carry no locality information except the sender's address, but almost invariably—and especially if it is disclosed that the material is of academic rather than economic interest—the prospector will readily supply locality details. It is likely that the meteorite was forwarded by a Yarri prospector, who, upon subsequent enquiry, stated that he had found it " 8 miles from Yerilla", leading to the additional note in the catalogue. A recent parallel would be the two small pieces of mesosiderite received in 1964 from a sender whose address was "Mount Padbury Station"; their precise site of find—nine miles distant from the Station homestead—was later willingly disclosed, resulting in a major recovery (Cleverly 1965).

The coordinates of Yerilla were 27° 27′S., 121° 13′E. and it was located 90 miles in direction 14° from Kalgoorlie.

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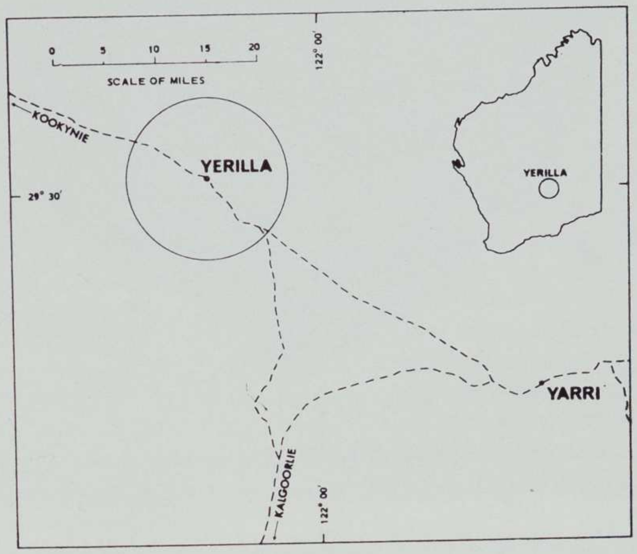

Figure 1.—Locality sketch map. The Yarri meteorite was probably found near the circle of eight miles radius centred on Yerilla.

Morphology

The single small mass had original dimensions ca 10 x 7.7 x 3.5 cm and weighed possibly 1600 g, but several small pieces had been hacked from it and the weight on receipt was about 1520 grams. The form is that of a thick, doubly arched slab (Fig. 2). The convex face is smooth except for a few shallow regmaglypts near its periphery and extending to the adjoining circumferential face; the largest and best defined regmaglypt, oval in outline, measures 3.5 x 2 x 0.3 cm deep. The concave face has three shallow, sub-circular pits, the largest 1 cm diameter; these and an irregular cavity in one end of the mass were probably localized by the burning out of sulphide or phosphide during atmospheric flight. The concave face had also a yellowish-brown, slightly glazed crust which contained abundant grains of quartz. This crust overlays a thin layer of iron oxide and several burn or weathering pits up to 4 mm diameter. The pits had been filled with loamy soil and the whole weakly "case hardened", suggesting a considerable age on earth.

A straight crack is traceable for 5 cm near one end of the mass and a cut face close to and sub-parallel with this crack shows a Widmanstätten pattern of two sets of bars in nearly right-angled relationship. The crack is therefore parallel to a cube plane of the taenite and is spatially equivalent to a 211 (trapezohedral)

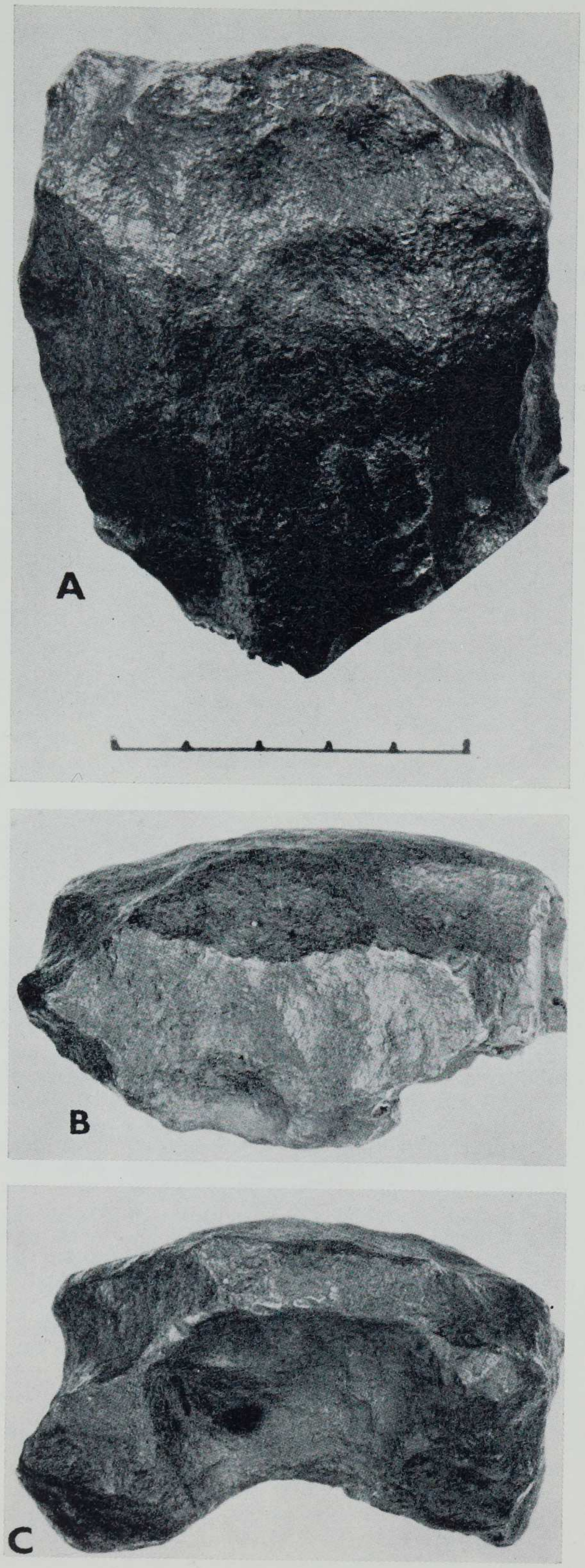

Figure 2.—Yarri meteorite. Scale bar in centimetres. A.—Convex face. Hammer dents, artificial damage and cut at lower end. B.—Side elevation (left side of A). C.—End elevation (upper end of A).

plane of the kamacite. This is a possible glide plane in kamacite, the composition plane for the Neumann twins, and a known parting (Palache et al 1944). Other cracks exposed on cut faces are occupied by iron oxide and are octahedral partings.

The specific gravity of a slice of 43 g measured by displacement of carbon tetrachloride is 7.69.

Chemical composition

Material showing schreibersite and some thin oxide veinlets at low magnification, but otherwise free of inclusions was used for analysis by classical wet methods. Weight percentages follow.

Fe	91.26
Ni	8.06
Co	0.45
Cu	0.022
C	Not found
P	0.170
S	0.004
	99.97

(Analyst: R. P. Thomas)

Structure and mineralogy

Cut faces on the end of the mass show Widmanstätten structure (McCall and de Laeter 1965, Pl. XIV c) except in recrystallized rim adjoining the convex and circumferential faces of the mass. The rim distribution suggests the convex face as the forward face in atmospheric flight. The rim is generally 2.5-4.5 mm wide, but narrows to 1 mm or less beneath regmaglypts (centres of unusually rapid ablation). In one section, rim is sharply bounded inward by octahedral partings which are now occupied by iron oxide (Fig. 4). Poor heat transmission across gaps which existed prior to atmospheric entry is the likely explanation for this and may be a partial explanation for the greater than usual width of rim in this section, since heat transmission would be hindered and the temperature intensified; hardness tests (series D, this paper) confirm these conclusions. Weathering losses are not responsible for the relatively narrow rim elsewhere since a reversed hardness gradient is still detectable there (hardness tests, series C).

A minor fault, traceable over a length of 3 cm at low magnification, crosses a kamacite bar almost at right angles and offsets also the fields of coarse plessite on each side of the bar (Fig. 3). After allowance for obliquity of the kamacite/plessite interfaces to the plane of the section, the apparent relative displacement is 0.5 mm at the middle of the fault and fades out towards each end.

Kamacite bars have approximate mean true width 0.75 mm as determined by the method of Frost (1965). Kamacite shows throughout the acicular (matte or epsilon iron) structure which is the aftermath of its momentary conversion to a denser polymorph during passage of a shock

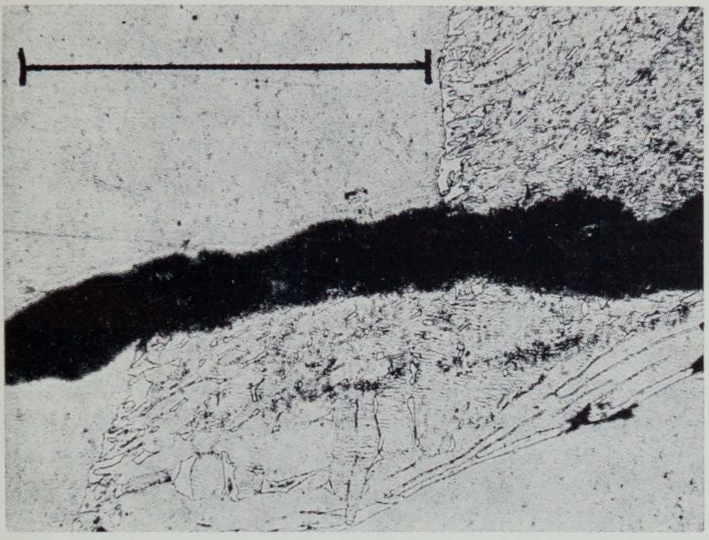

Figure 3.—Photomicrograph showing faulting of a kamacite/plessite interface in Yarri meteorite. Scale bar 1 mm.

wave of intensity in the range 130-750 kb (Smith 1958, Maringer and Manning 1962). Neumann lines may show gentle curvature and sharp transverse hatching (Heymann et al 1966). The acicular structure, faulting and other fracturing may be attributed to some extra-terrestial event since the impact shock of a small mass is quite ineffectual. Evidence that the octahedral partings predate atmospheric flight has been given above; evidence in the case of the acicular structure is provided by its sharp boundary with recrystallized rim (Maringer and Manning op. cit.).

Taenite strips have apparent width 0-0.05 mm, commonly 0.02 millimetre. Etching with nital reveals small patches of the spotted or darkened variety (Perry 1944) within some grains, or forming a zone just inside the edge, but always the rim is of clear taenite (Comerford et al 1968, Fig. 2). Octahedral slip lines reported by Maringer and Manning (1962) in the taenite of the shocked Grant meteorite could not be detected with the recommended etchant.

Plessite fields include both coarse (light) and dense (dark) types. Larger fields are of the coarse type and may be either lamellar or micro-granular. The dense type occurs as small independent fields or by the transformation of nickel-enriched taenite grains at the corners and edges of the coarse fields. Some of the larger taenite areas also gave rise to oriented, barrel-shaped or spindle-shaped kamacite; when dense plessite is also present within such grains clear taenite rims the kamacite as well as the edge of the field.

Schreibersite is of very variable shape, often elongate, curved or more complex. It has usually nucleated in kamacite/kamacite interfaces including those of the coarse plessite, but it also forms narrower bodies between kamacite and the strip taenite or the taenite rim of plessite. Dimensions are up to 0.1 × 3 millimetres. Rhabdites were not seen; nor could they be found in the residue from the solution of meteorite in dilute cold nitric acid.

Troilite may be represented by a few minute grains of sulphide indicated by sulphur prints. The sulphur of the analysis is equivalent to less than 0.02% troilite by volume.

Schreibersite-metal eutectic occurs as an amoeboid area with emulsion texture, the minute rounded and lamellar bodies of metal tending to be concentrated within parallel bands in the phosphide. It is within recrystallized rim at what was formerly an interface between kamacite bars (taenite bodies occur at the same interface), extends 0.7-1.3 mm from the edge of the meteorite, and is backed by an octahedral parting 1.2 mm distant and forming the boundary of the recrystallized rim (Fig. 4). The melting point of the phosphide-metal eutectic is ca 1000°C (Brentnall and Axon 1962) and such temperature is exceeded to a depth within an iron of 1 mm during atmospheric flight (Lovering et al 1960, Fig. 5), and probably to greater depth in the special circumstances here present. Thus, for example, the temperature necessary for recrystallization of kamacite is 770 ± 20° C (Maringer and Manning 1959), but the limit of recrystallization marking the attainment of that temperature lies about twice as deep as is suggested by Lovering et al. An adequate temperature was therefore available for the development of a small pocket of phosphide-metal melt which escaped ablation and cooled rapidly in the lower atmosphere.

Volume composition

The statement below is not a mode as it includes alpha iron and gamma iron at minimum equilibrium temperature (T_o) according to the scheme of Massalski and Park (1962, 1964). Alpha iron is the kamacite of the Widmanstätten bars and of the coarse plessite; gamma iron is the remainder of the metal. This is simpler than the general case because, in the Yarri meteorite, all the kamacite in coarse plessite has substantially larger dimensions that the coarsest platelets of "interior" plessite regions and is therefore regarded as alpha iron; also, in the few cases in which they occur, areas of kamacite within taen-

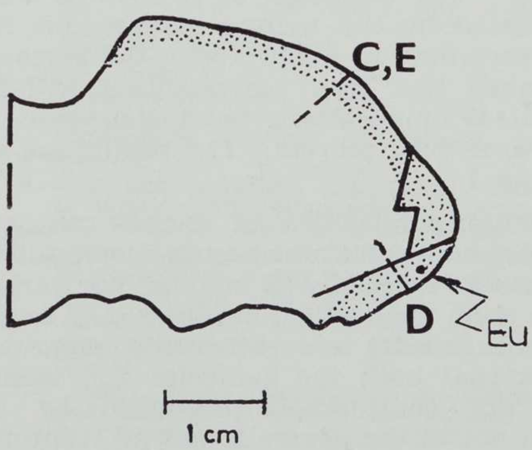

Figure 4.—Portion of slice of Yarri meteorite, anterior face of flight upward, recrystallized rim stippled. Rim bounded in one section by octahedral partings. Hardness traverses C, D, E lettered. Eu indicates eutectic.

ite are of inferior dimensions to that in coarse plessite and can therefore be recorded as gamma iron. Volume percentages determined by integrating stage are as follows.

Alpha iron at T_o	93.6
Gamma iron at T_o	4.9
Schreibersite	1.3
Iron oxide	0.2

Temperature estimates do not accord well with those of Massalski and Park (1962). From the analysis, the nickel content of the nickel-iron is 8.11% which gives T_i (the temperature at which alpha-phase separation began) as 728°C; the proportion of gamma-phase in total metal is 0.05 and application to the phase diagram gives T_o as 438°C. The amount of gamma-phase and the interval T_i - T_o would be more appropriate to a coarse octahedrite. As a check, the gamma-phase was subsequently re-determined by point counting, and the result was slightly lower than that given above, further increasing the discrepancy.

Microhardness tests

Microhardness indentation tests were made to examine the effects of shock and aerodynamic heating on the hardness of kamacite and taenite. A Leitz Miniload tester was used with the following procedure except where otherwise stated: Vickers diamond, 100g load, time of descent 15 seconds, rest period 15 seconds, 10 indentations of an acceptable degree of perfection, diagonals measured twice, the result stated as the mean and standard deviation thus—212(8).

Series A.—The hardnesses of kamacite and taenite remote from recrystallized rims were measured in Yarri and in three other medium octahedrites of comparable nickel content. Test sites were located in the mid-lines of bars; surfaces were minimally etched for recognition of phases and grain boundaries. Irons used for comparison were Roebourne, 8.04% nickel (Lovering et al. 1957), Youanmi, 8.08% nickel (Simpson 1938) and Trenton, 8.05% nickel (Axon 1967). Trenton, like Yarri, has acicular shock structure; Youanmi is only "normally" shocked. The condition of Roebourne was not appreciated by the writers at the time it was used; according to Axon (1968), the kamacite of Roebourne has been recrystallized within the original Widmanstätten band structure by an extra-terrestrial process. The results are shown in Table 1.

Although similarities of nickel content and structure do not fix precisely the compositions of the phases (especially of taenite) nor variability within them upon which hardness may be dependent, the results are sufficiently separated to suggest that both the kamacite and taenite of Yarri are considerably hardened by shock, though not to the degree found in Trenton. Recrystallization appears to have removed effectively any shock hardening which might initially have been present in Roebourne.

TABLE 1

Vickers hardness numbers (100g) for kamacite and taenite in octahedrite irons

	Kamacite	Taenite
Roebourne	195 (8)	212 (9)
Youanmi	212 (8)	240 (11)
Yarri	299 (8)	390 (9)
Trenton	364 (7)	482 (15)

Series B.—Since compositional and hardness variations within kamacite—if present—are likely to be related to interfaces with taenite, ten traverses of five tests were made in the kamacite of Yarri, the test sites of each traverse equally spaced from near an edge to near the mid-line of a bar. These five positioned samples, each of ten tests, had means in the range 296-303 and mathematical treatment indicated no significant difference from the mid-line result—299(8). Significant hardness variation dependent upon location within the bars is thus unlikely to be found by the adopted procedure; the result is a desirable prerequisite to the series which follows.

Series C.—Three parallel traverses of tests were made in kamacite from the interior of the mass across recrystallized rim of width 2.2 mm to the edge (Fig. 4), with intermediate traverse lines in reserve for repetition of unacceptable tests. The results are shown in Fig. 5A, in which each point is the result of three only acceptable tests.

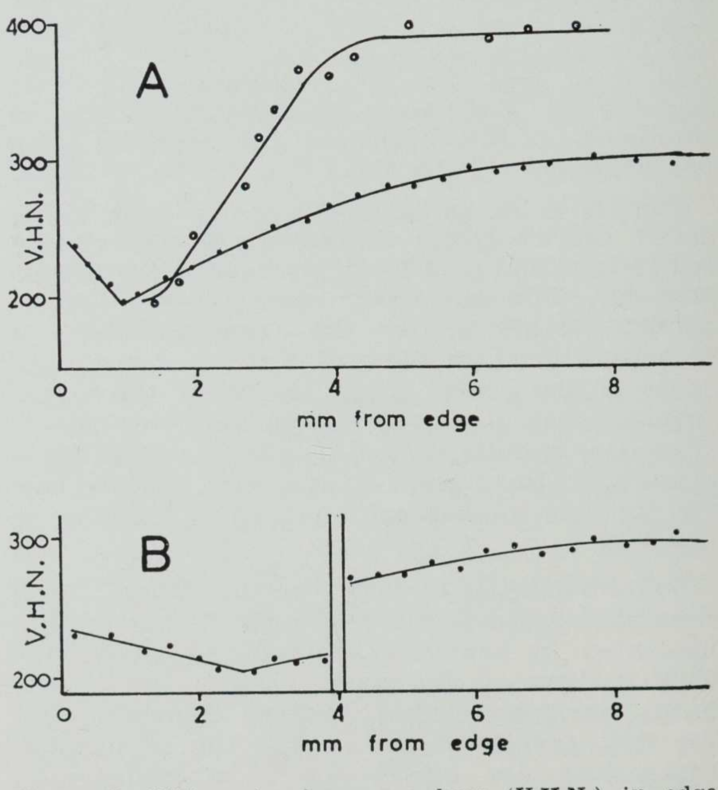

Figure 5.—Vickers hardness numbers (V.H.N.) in edge zone of Yarri meteorite. A.—Lower curve kamacite, upper curve taenite. B.—Kamacite curve with discontinuity at an octahedral parting.

Softening of kamacite is first detectable 7 mm inside the edge and the hardness declines regularly without evident discontinuity at the margin of the recrystallized rim to V.H.N. 200 (a figure comparable with "normally" shocked kamacite), releasing the strains of shock and of the recrystallization. Hardness reversal in the outermost 1 mm—compare Maringer and Manning (1959, 1960)—may be related to a reversed temperature gradient following attainment of the speed of fall, so that a zone inside the edge remained hot longer than the metal on each side of it and was more completely annealed.

Some Vickers hardness numbers may now be reviewed. Metal of the ablation deposit on Youanmi is included to improve the spectrum of values. The high hardness of the edge material on Youanmi was early noted by Simpson (1938); the hard "graduated band" and "altered area" found upon a Henbury iron by Dalton (1950) may also have been an ablation deposit.

Kamacite, "normally" shocked	ca 210
Kamacite, moderately shocked	ca 300, 360
Metal of ablation deposit	(mean) 350
Kamacite, recrystallized, annealed	(min.) 200

Series D.—Traverses in kamacite similar to series C were made where an octahedral parting bounded the recrystallized rim (Fig. 4). The results (Fig. 5B) show by the discontinuity of the curve and by the depth within the mass at which hardness reversal occurs that the parting hindered the inward flow of heat both during ablation and during cooling in the lower atmosphere.

Series E.—A traverse similar to series C and in the same location was made in taenite but because of limited availability of test sites, some of the results (Fig. 5A) are of single tests, others the means of two or three tests. Softening is first detectable 4.5 mm from the edge and hardness falls rapidly over a distance of 3 millimetres. In the outmost 1.5 mm, only some scattered readings were possible. All results were in the range V.H.N. 191-207 and no trend was recognised.

From Table 1 it is seen that the range of hardness shown by kamacite is 169 and by taenite 270. Taenite may therefore be the more sensitive though not such an obvious shock "barometer", at least for irons of comparable chemistry in the moderately shocked range.

Relationship to other irons

The literature of meteorites found in the Eastern Goldfields region of Western Australia was searched for irons which might show relationship to Yarri; two warranted brief re-examination.

The resemblances of Yarri to Nuleri were found to be superficial. The "damascened" structure of Simpson (1907)—"hatchings" of Brezina (1914)—are not the typical acicular shock structure and the metal shows little, if any, hardening—V.H.N. 232(8). The only available analysis showed a nickel content unacceptably low for an octahedrite iron, and nickel was re-determined as 7.32% (analyst R. P. Thomas)— a figure still significantly lower than Yarri.

The Youanmi iron has much the same nickel content and structure as Yarri but the kamacite shows distinct flecking and is unhardened (Table 1).

Thus none of the irons known from within 500 km of Yerilla show close resemblances to the Yarri medium octahedrite.

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